LBL-23426

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Accelerator & Fusion Research Division

LBL--23426

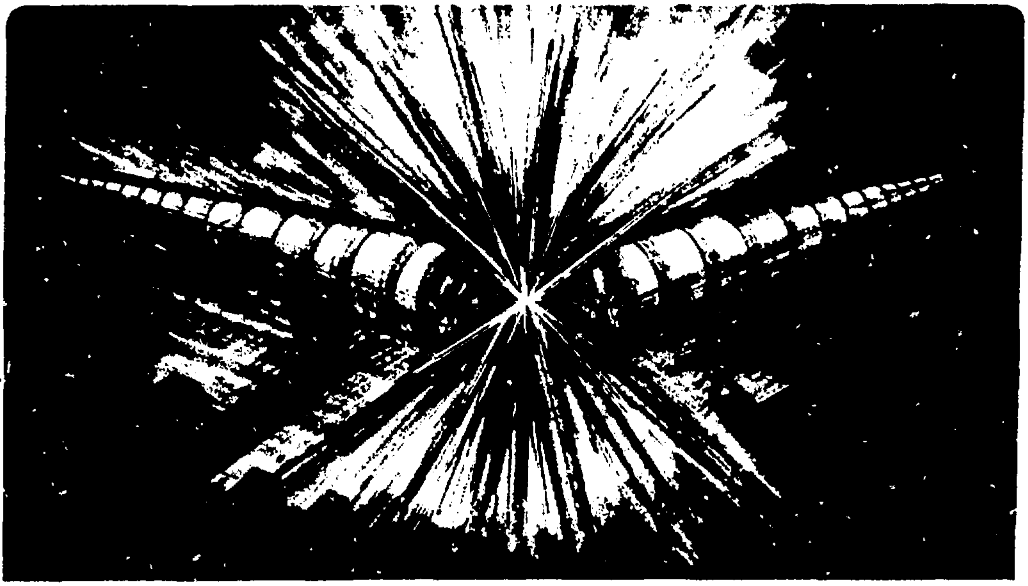
DE87 014127

Presented at the ICFA Workshop on Low Emittance Beams, Upton, NY, March 20-25, 1987

PERFORMANCE COMPARISONS OF LOW EMITTANCE LATTICES

J.-P. Delahaye and M.S. Zisman

May 1987



Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

LBL-23426
ESG-30

PERFORMANCE COMPARISONS OF LOW EMITTANCE LATTICES*

Jean-Pierre Delahaye
PS Division
CERN
Geneva, Switzerland

Michael S. Zisman
Accelerator and Fusion Research Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720 USA

May 1987

*This was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, U.S. Dept. of Energy, under Contract No. DE-AC03-76SF00098.

Performance Comparisons of Low Emittance Lattices

Jean-Pierre Delahaye
PS Division
CERN
Geneva, Switzerland

and

Michael S. Zisman
Accelerator & Fusion Research Division
Lawrence Berkeley Laboratory
Berkeley, California 94720
U.S.A.

Introduction

In this paper, we present the results of a performance analysis of several low emittance electron storage ring lattices provided to us by various members of the Lattice Working Group. Altogether, four lattices were investigated.[1] They will be referred to in this paper as Lattices 1, 2, 3, and 4. (This rather unimaginative notation is intended to be at least somewhat mnemonic. The beam energies of the four lattices are, respectively, 1.1, 2, 3, 4 GeV.) A brief summary of the lattice parameters relevant to this study is given in Table I. Further details may be obtained from the reports of the Lattice Working Group elsewhere in these proceedings.

There are two different functions being considered for the low beam emittance rings discussed here. The first is to serve as a Damping Ring (DR), i.e., to provide the emittance damping required for a high energy linear collider. The second is to provide beams for a short wavelength Free Electron Laser (FEL), which is envisioned to operate in the wavelength region near 40 Å.

As we will see, the former possibility seems at present to be more easily achievable than does the latter.

The performance issues we will study include an estimation of the longitudinal emittance expected for each lattice based on the effects of the longitudinal microwave instability, an estimation of the transverse emittance growth of the (required) dense bunches under the influence of intrabeam scattering (IBS), and an estimate of the Touschek lifetime. (This latter issue is, in principle, a minor one for the damping ring application we are concerned with here, but it is relevant for an FEL ring and it is in any case important to verify that the lifetimes do <u>not</u> become unreasonably short.)

The analysis described here has been carried out with the LBL accelerator physics code ZAP.[2]

<u>Longitudinal Emittance</u>

As a "figure of merit" for the longitudinal case, we will use the quantity defined by Pellegrini[3] as longitudinal brilliance:

$$\mathcal{B}_{\ell} = \quad I_p/(\gamma\sigma_p/p) \tag{1}$$

where I_p is the allowable peak current (which we take to be determined from the longitudinal microwave instability) and σ_p/p is the rms momentum spread. For the damping ring application, we do not require that there be no bunch lengthening at all, but merely that the longitudinal growth be consistent with the normalized longitudinal emittance specification of Palmer,[4] i.e., we demand that

$$\varepsilon_{\ell n} = \quad \gamma\sigma_{\ell}\sigma_p/p \;\; \leq 0.025 \text{ m} . \tag{2}$$

For the FEL application, at E = 1 GeV, the corresponding value is $\varepsilon_{\ell n}$ = 0.001 m.[3]

Our estimate of the longitudinal peak current is given by[2]

$$I_p = \frac{2\pi|\eta|(E/e)(\beta\sigma_p/p)^2}{|Z/n|_{eff}} \tag{3}$$

where η is the phase-slip factor and $|Z/n|_{eff}$ is the longitudinal impedance seen by the beam bunch. As a "standard" value, we take the effective longitudinal impedance to be 0.2 Ω. This value, while better than typically reported for today's storage rings, is felt to be achievable in a modern ring, provided that enough care is taken in the design and fabrication of all storage ring components.

For short bunches, experimental observations[5] seem to suggest that the effective longitudinal impedance $|Z/n|$ seen by the beam at high frequencies (which is the regime of relevance to bunch lengthening) is reduced substantially from that in the low frequency regime. (Such an impedance roll-off at frequencies beyond the beam pipe cutoff would be a natural consequence of the frequency dependence of any low-Q broadband resonator.) In ZAP, this effect is taken into account for bunches having $\sigma_\ell \leq b$ (where b is the beam pipe aperture radius, taken here to be 1.25 cm) by reducing the broadband impedance according to:[2]

$$|Z/n| = |Z/n|_o \, (\sigma_\ell/b)^{1.68} \quad . \tag{4}$$

We refer to this phenomenological approach as "SPEAR scaling." For very short bunches, the impedance reduction described by Eq. (4) is substantial. In such a case the bunch lengthening is expected to be dominated by the so-called free-space impedance (in ohms) of[2]

$$|Z/n|_{FS} = 300 \, (b/R) \tag{5}$$

where R is the storage ring radius. The free-space impedance, which is also generally on the order of a few tenths of an ohm for a small ring, gives a practical lower limit to the longitudinal impedance that can be achieved.

Results of ZAP calculations for the four lattices are summarized in Table II. For the purposes of a damping ring, all of the candidate lattices appear to be suitable. We can see in Table II that, for an rms momentum spread of 1×10^{-3} or less, we are able to achieve a normalized longitudinal emittance of 0.025 m or better at a bunch intensity of at least 1×10^{10} per bunch. We note, however, that the values of B_ℓ that correspond to the Palmer[4] DR criterion are a factor of 5-10 lower than the value of $\mathrm{B}_\ell = 100$ specified by Pellegrini.[3] It is also important to note here that the parameters for Lattice 1 imply a low frequency, high voltage RF system. This clearly would involve practical difficulties in a relatively small ring.

There is an implicit assumption in our calculations that we can actually achieve an emittance coupling of 1% with low emittance lattices such as the ones considered here. Given the very strong focusing required to reach these emittance values, and the precision with which magnets can reasonably be fabricated and aligned, this is not certain. We note, however, that the VUV ring at BNL has reportedly achieved emittance coupling values below 1% (albeit with a higher emittance lattice), so we clearly cannot consider this to be an unreasonable specification at this stage.

If we consider the use of such rings in a high-gain FEL mode, at a wavelength of, say, 40 Å, the results are, unfortunately, less encouraging. In this case, we require small values for both the bunch length (to keep the proper phase relationship in the undulator) <u>and</u> the momentum spread (to avoid substantial gain reduction from Landau damping). The required value for the rms momentum spread for this application is about 5×10^{-4}, which should be achievable. However, the bunch length requirement of $\sigma_\ell \approx 1$ mm is more difficult. In the present cases (at their nominal operating energies), it was not possible to achieve a bunch length as low as 1 mm, even with a rather high frequency (1000 MHz) RF system. Even if we ignore any issues of turbulent bunch lengthening (which, because of the free-space impedance, is probably <u>not</u> a reasonable thing to do), the "natural" bunch length is given by:

$$\sigma_{\ell} = \frac{\eta R}{\nu_s} (\sigma_p/p) \qquad (6)$$

which means that, for a moderate sized ring, a momentum compaction factor of about 1×10^{-4} is needed to achieve the requisite bunch length. At this level, higher-order momentum compaction terms may be significant.

However, if we scale the parameters of Lattice 4 down to an operating energy of 1 GeV, as would be typical of the FEL application, the $\varepsilon_{\ell,n}$ requirement can be easily met. There are practical difficulties with this approach, however, in that: (*i*) the damping time becomes quite long ($\approx$ 0.6 s); and (*ii*) the attainable peak current (limited by the microwave threshold) is quite low ($\approx$ 5 A). As we will see in the next section, this scenario also leads to a large, but tolerable, growth in the transverse emittance.

<u>Transverse Emittance</u>

Because of the very high bunch densities involved here, we must ascertain that there is no significant emittance growth from intrabeam scattering (IBS). To do this, we use ZAP[2] to calculate the equilibrium emittance of each ring including the effects of IBS. The results are given in Table III. Included in Table III are values of the 6-dimensional brightness factor of Pellegrini,[3] defined as:

$$\mathcal{B}_6 = \mathcal{B}_{\ell}/(\varepsilon_{n,h}\, \varepsilon_{n,v}) \quad . \qquad (7)$$

We see that there is essentially no emittance growth for Lattice 1, about 10% growth for Lattices 2 and 3, and nearly a factor of 2 growth for Lattice 4. This pattern, of course, reflects mainly the difference in natural emittance values in the various cases (along with the much greater bunch length chosen for Lattice 1).

As mentioned, we also examined (briefly) the case of lowering the operating energy of Lattice 4 to 1 GeV to see if this approach would be useful in the context of an FEL ring. In this circumstance, the damping time of the ring increases by a factor of 64, and the bunch length (at $\sigma_p/p = 5 \times 10^{-4}$) is only 0.6 mm. At full coupling, the transverse emittance grows by a factor of 50 from its natural value. Nonetheless, the resultant normalized emittance value is only 0.5×10^{-6} π m-rad, which is consistent with what is required.[3] The corresponding value for $\mathcal{B}_6$ here is 0.22×10^{14}, which is lower by about a factor of five than the value specified by Pellegrini.[3]

Touschek Lifetime

For completeness, we also checked the Touschek lifetime for each of the lattices studied. The results are summarized in Table IV. In every case, the calculated lifetime would be suitable for use as a damping ring. Lattices 1 and 2, however, would probably be less painful to commission than Lattices 3 and 4.

In the FEL case, where we consider running Lattice 4 at a reduced energy of 1 GeV, the (unnormalized) beam emittance is significantly larger than at 4 GeV, and the Touschek lifetime becomes sufficiently long that it is not an issue.

Comments

There are several areas where more work is clearly required to ascertain that the assumptions made here are, in fact, realistic. First of all, it will clearly be worthwhile to refine the beam specifications for both the DR and FEL cases. Especially for the latter case, the limits on longitudinal emittance (that is, both bunch length and momentum spread) are so severe that it does not at present seem practical to meet them while simultaneously maintaining a reasonable beam current and a reasonable damping time.

In addition, for both applications of a low emittance storage ring it is necessary to have a better handle on the impedance issue. For example, we must try to understand what limits the attainable value of the longitudinal broadband impedance in existing storage rings, and how to improve what can be obtained. That is, we must answer the question of what is the minimum practical value of Z/n (including RF cavities, kickers, bellows, valves, etc.). Secondly, we must better understand the issue of impedance roll-off for short bunches (i.e., high frequencies). Finally, we must deal carefully with the question of free-space impedance, and how it manifests itself in the turbulent bunch lengthening phenomenon.

As mentioned, it is not completely clear that the low emittance lattices considered here can be run with an emittance coupling as low as 1%. Further understanding of the limitations to the achievable emittance coupling would obviously be helpful. If a 10% ratio were assumed, for example, it would modify our beam emittance requirements for the DR case.

Although they are not yet issues, we should not forget that, if multibunch operation were considered for either the DR or FEL application, the topics of ion trapping and coupled-bunch instabilities would have to be explored. Given the difficulties in achieving suitable intensities while maintaining the other beam parameters, it seems likely that multiple bunch scenarios will be investigated as a way to mitigate some of the problems associated with beam collective effects.

Summary

From the results presented here, we find that the example lattices can come fairly close to meeting the DR specifications (based upon an assumed 1% emittance coupling) proposed by Palmer.[4] We can get a beam intensity of 1×10^{10} per bunch, with a normalized emittance of about 5×10^{-6} π m-rad transversely and about 0.025 m longitudinally. Emittance growth from IBS is generally not negligible, but it is not so great as to compromise the required emittance value. This factor will be a limit, however, for normalized emittance values as low as 1×10^{-6} π m-rad.

The possibility of achieving the required longitudinal emittance for the FEL application by reducing the operating energy of a high energy lattice to 1 GeV was also considered. Although the transverse emittance growth under these conditions is large (about a factor of 50 increase from the natural emittance), the resultant normalized emittance is still only about 0.5×10^{-6} π m-rad for a fully coupled case. Thus, it appears that we can come reasonably close to reaching the longitudinal and transverse emittance goals for the FEL case, but at rather low currents and with a long damping time. Whether this approach is at all interesting to the FEL community is not yet clear.

Acknowledgments

We would like to thank the various members of the Lattice Working Group, and especially A. Ruggiero and J. Murphy for many informative discussions. The help of R. Maier and B. Craft in carrying out the ZAP calculations is also appreciated. Finally, we want to acknowledge a stimulating 3:00 a.m. discussion on lattice design with G. Vignola.

One of us (MSZ) is supported by the U.S. Dept. of Energy, under Contract No. DE-AC03-76SF00098.

References

1) The lattices were provided by: R. Palmer (Lattice 1); A. van Steenbergen (Lattice 2); J. Murphy (Lattice 3); A. Ruggiero (Lattice 4).

2) M.S. Zisman, S. Chattopadhyay, and J.J. Bisognano, ZAP User's Manual, LBL-21270, December, 1986.

3) C. Pellegrini, Beams for Colliders or FELs, presented at this Workshop.

4) R. Palmer, Low Emittance Beams for Colliders, presented at this Workshop.

5) A.W. Chao and J. Gareyte, Scaling Law for Bunch Lengthening in SPEAR-II, SLAC Note SPEAR-197, PEP-224, December, 1976.

Table I.

Major Lattice Parameters

Lattice		1	2	3	4
Type[a)]		W	CF	FODO	FODO
E	[GeV]	1.1	2	3	4
C	[m]	125	120	135	341
α	[10^{-3}]	1.7	1	1	0.2
τ_E	[ms]	3.7	2.6	3.8	10.8
f_{RF}	[MHz]	25	500	1000	1000
V_{RF}	[MV]	0.5	2	2	2

a) W denotes a wiggler (alternating positive and negative bend) lattice; CF is a combined-function lattice.

Table II.

ZAP Results for Longitudinal Parameters

Lattice		1	2	3	4
σ_ℓ	[mm]	19.1	3.7	3.3	2.8
σ_p/p	[10^{-3}]	0.6	1.0	1.0	1.0
$\varepsilon_{n,\ell}$	[m]	0.025	0.014	0.019	0.022
I_p	[A]	21	74	114	77
N_b	[10^{10}]	2.1	1.4	2.0	1.1
$\mathcal{B}_\ell$	[A]	16.3	19.0	19.4	9.8

Table III.

ZAP Results for Transverse Parameters

Lattice		1	2	3	4
$\varepsilon_{0,n}$	$[10^{-6}\ \pi$ m-rad]	3.0	6.8	6.2	1.2
ε_n	$[10^{-6}\ \pi$ m-rad]	3.0	7.7	6.7	2.1
$\mathcal{B}_6$	$[10^{14}$ A/m^2]	1.80	0.32	0.43	2.20

Table IV.

ZAP Results for Lifetimes

Lattice		1	2	3	4
τ_T	[hr]	50	1.7	0.11	0.11
Δp_{RF}	[%]	8.8	4.5	2.1	2.4